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DEPARTMENT OF DEFENCE

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AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

AERODYNAMICS NOTE 395

REDUCTION IN SWING OF A SONAR BODY WINCHED FROM THE SEA BY A HELICOPTER

by

N. E. GILBERT

Approved for Public Release

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SUMMARY

When a sonar body is winched from the sea by a helicopter, growth in amplitude of oscillation of the body occurs. This is demonstrated using a two-dimensional mathematical model. To avoid the possibility of collision with the helicopter, an automatic procedure is proposed in which the body is alternately raised and lowered during defined periods of each oscillation. When the prescribed degree of damping is achieved, the body is raised continuously to the trail position. Performance of the method is judged by the amount of additional raise time required. The procedure is applied to the sonar system used on the Royal Australian Navy's Sea King Mk.50 helicopter.

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16. *ABSTRACT*

When a sonar body is winched from the sea by a helicopter, growth in amplitude of oscillation of the body occurs. This is demonstrated using a two-dimensional mathematical model. To avoid the possibility of collision with the helicopter, an automatic procedure is proposed in which the body is alternately raised and lowered during defined periods of each oscillation. When the prescribed degree of damping is achieved, the body is raised continuously to the trail position. Performance of the method is judged by the amount of additional raise time required. The procedure is applied to the sonar system used on the Royal Australian Navy's Sea King Mk.50 helicopter.

CONTENTS

NOMENCLATURE

K	Cable speed direction control switch, $= -1$ for raise, $= 0$ for hold, $= 1$ for lower.
P_B	Point of attachment of cable to sonar body.
P_H	Suspension point of cable.
P_b	Position of centre of gravity of sonar body.
P_t	Trail position on cable—at hover height for cable vertical.
T	Cable tension.
a	Distance between P_B and P_b.
d_f	Distance between P_H and funnel rim.
d_t	Distance between P_H and P_t.
e	Damping procedure control switch; if $e = 0$, then raise, lower, or hold to reduce swing amplitude; if $e = 1$, then raise or lower continuously.
f_K	Defines $\dot{s}_m$ as a function of s_m for each value of K.
g	Gravitational acceleration.
h	Height parameter, $h_a - h_s - h_m$.
h_a	Actual hover height.
h_m	Clearance margin between bottom of sonar body and sea surface.
h_s	Length of sonar body.
j	Cable length correction switch ($= 0$ if correction not completed, $= 1$ if completed).
m	Mass of sonar body.
n_ℓ	Total number of times sonar body is lowered.
n_s	Counter for number of half-period oscillations (see Appendix A).
s	Effective freely moving cable length ($= s_m + s_c$).
s_1	Arbitrary distance.
s_c	Correction to measured cable length.
s_m	Measured cable length between P_t and P_B.
t	Time from last 'reset'.
t_1	Estimated quarter-period of oscillation for simple pendulum ($= \frac{1}{2}\pi/\hat{\omega}$).
$t_{\ell A}, t_{\ell B}, t_{rA}, t_{rB}$	Values of t at which lowering and raising is commenced or stopped (see Fig. 4).
t_r	Total raise time
x, z	Horizontal (positive in direction of helicopter heading) and vertical (positive down) displacement coordinates of P_b.
Δt	Sampling time increment.

Δt_h, Δt_ℓ, Δt_r	Times for holding, lowering, and raising (see Fig. 4).
θ	Angular displacement of cable at P_t from vertical (positive in direction of helicopter heading).
θ_0	θ at $t = 0$.
θ_1	Estimate of $\lvert\theta\rvert$ at $t = t_1$.
θ_{aft}, θ_{for}	Aft and fore limits of θ at which cable touches funnel rim.
θ_e	Maximum angular magnitude, as a function of s_m, defining satisfactory raise envelope.
θ_{eo}	θ_e at $s_m = 0$.
θ_{lim}	Mean value of magnitude of θ_{aft} and θ_{for}.
θ_{old}	θ at previous sampling time.
λ_h	Hold time ratio, $\Delta t_h/t_1$.
$\lambda_{\ell r}$	Lower to raise time ratio, $\Delta t_\ell/\Delta t_r$.
ω	Angular frequency of oscillation, $(g/s)^{\frac{1}{2}}$.
$(\dot{\ })$	Derivative with respect to time.
$(\hat{\ })$	Estimated mean value over half-period of oscillation.
(0)	Initial value, e.g. $s_m(0)$, $\theta(0)$.

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1. INTRODUCTION

To detect submarines, naval helicopters often use a sonar body which is lowered by cable into the water. On winching the sonar body from the sea, under certain conditions it is possible for the amplitude of oscillation of the body to increase to the point where collision with the helicopter fuselage occurs. Such collisions, called 'ball strikes', can cause damage both to the helicopter and to the fragile components of the sonar body. Since most ball strikes occur when sea conditions are very rough, it is likely that large surface waves cause a significant increase in amplitude of oscillation of the sonar body as it breaks the sea surface. On raising the sonar body to the trail position, just below the helicopter, it is shown that the amplitude of oscillation increases. Poor helicopter hover stability may further aggravate the problem, but this factor is not considered. To avoid ball strike, it is necessary to dampen the amplitude of oscillation when the sonar body is clear of the water. Using energy principles, a method of achieving this is presented in which the sonar body is alternately raised and lowered during defined periods of each oscillation. The two-dimensional case is studied for the sonar system used on the Sea King Mk.50 helicopter. The method could easily be extended for the more realistic three-dimensional motion observed in which the sonar body describes an elliptic path that is generally fairly eccentric. However, the two-dimensional treatment adequately demonstrates the principles involved and gives total raise time penalties that are also typical of three-dimensional motions, since the periods of oscillation are similar. It should be noted that the method may cause excessive cable wear through raising the sonar body while the cable touches the funnel rim, but this could be reduced by fitting rollers to the funnel rim.

2. MATHEMATICAL MODEL

In simulating the complete procedure for raising the sonar body, it would be difficult to model the behaviour of the system while the body is submerged without formulating an adequate model of sea waves. Such a model could only be developed using statistical concepts. The system is therefore modelled only while raising in air, with various initial conditions representing the net effect on the system of raising through water. Generally, in air, both the gravitational and aerodynamic drag forces acting on the sonar body will be much greater than those acting on the attached cable so that the latter may be neglected. Other effects neglected are cable twist, cable elasticity, the induced mass of both sonar body and cable, and all frictional forces. Probably the most basic representation of the system is that of a simple pendulum with a varying pendulum length, where the only forces acting are cable tension, sonar body weight, and the inertial forces on the sonar body.

As a preliminary investigation, a fairly comprehensive two-dimensional model of the Bendix AN/AQS-13B sonar system[1] used in the R.A.N.'s Sea King Mk.50 helicopters was formulated and then programmed using the simulation language CSMP-10(ARL).[2-5] In addition to forces considered necessary in the above basic representation, the model included (a) aerodynamic forces acting on the sonar body, (b) acceleration (positive or negative) of the body caused by changing raise speed (i.e. cable acceleration effect), (c) a freely pivoting attachment between the cable and sonar body (i.e. compound pendulum effect), and (d) the effect of the cable touching the funnel rim (i.e. funnel snagging). Aerodynamic forces were included, using drag force, lift force, and pitching moment coefficients obtained from wind tunnel tests performed at A.R.L. on a 0·75 scaled sonar model.[6] The aerodynamic force and cable acceleration effects were found to be negligible. The compound pendulum effect resulted in only small amplitude oscillations superimposed on the main lower frequency oscillation. Representation of the system by a simple pendulum with a varying pendulum length was therefore judged to be adequate for the purposes of the model. When the cable touches the funnel rim, the pendulum length is

effectively shortened, thus reducing the period of oscillation and increasing the amplitude of oscillation so as to conserve potential energy. Hence this effect is retained in the model presented below.

Consider then the simple pendulum representation shown in Figure 1. The effective freely moving cable length, s, is given by

$$s = s_m + s_c \tag{1}$$

where

$$s_c = a + d_t \qquad \text{if cable free of funnel} \tag{2a}$$

$$= a + d_t - d_f \qquad \text{otherwise} \tag{2b}$$

Resolving forces radially and tangentially at P_b,

$$T = \text{mg} \cos \theta + \text{ms}\, \dot{\theta}^2 \tag{3}$$

$$\ddot{\theta} = -2\dot{s}\dot{\theta}/s - (g/s) \sin \theta \tag{4}$$

which is the model used in all simulations presented below. Given a sufficiently large initial angular displacement, Figure 2, which shows a time history of the body displacement coordinates (x, z), demonstrates how an unsuitable raising procedure would result in ball strike.

The observed increase in amplitude of oscillation as the body is raised may be explained using the principle of conservation of energy. Neglecting frictional forces, the work done by the reeling machine in winding the sonar body in by a given amount is balanced by a gain in both kinetic and potential energy of the sonar body. The least amount of work required to raise the body through a distance s_1 is Ts_1. When the angular velocity of the body is zero, this work equals the gain in potential energy of the body, i.e. mg $s_1 \cos \theta$. However, when the angular velocity is non-zero, additional work is required because of the increased tension given by inclusion of the term ms$\dot{\theta}^2$ in Equation (3). This additional work is balanced by a gain in energy which, together with a shortened pendulum length, results in larger amplitude motion. The greatest additional energy input is obtained when $\dot{\theta}$ is greatest, i.e. when the cable is vertical, and the least when $\dot{\theta} = 0$, i.e. at maximum angular displacement. Hence, to minimize the increase in swing amplitude, it is desirable to raise only when close to maximum angular displacement. Using similar energy considerations, it may be shown that the greatest effect in reducing swing amplitude is achieved by lowering only when close to the vertical. This suggests that a convenient way to stabilize excessive swing would be to alternately raise and lower the body until the swing is sufficiently damped; the body could then be raised safely to the trail position. Such a procedure could be operated manually, given sufficient instrumentation and control in the helicopter. In the Sea King, cable length, s_m, and angular displacements in pitch and roll of the cable at its suspension point are measured. However, s_m is not displayed and funnel snagging results in a low cut-off in the maximum angular displacements displayed (usually between 9° and 15°). It would be desirable therefore, as well as much more efficient, to incorporate an automatic system capable of handling a wide range of possible conditions. Such a system is now described.

3. PROCEDURE FOR REDUCING AMPLITUDE OF OSCILLATION

It can be seen in Figure 2 that ball strike is assumed to occur when the amplitude of oscillation is 90°. In practice though, this value will depend on the geometry of both the sonar body and helicopter fuselage and will generally be somewhat less than 90°. When raising the sonar body from the trail position to its seat position inside the funnel, the oscillation amplitude must be very small (usually less than 5°). It is generally desirable therefore to set a maximum amplitude value, θ_{eo}, at the trail position (where $s_m = 0$) that is close to the small value needed for seating the sonar body; otherwise, excessive time may be required for natural damping through aerodynamic and frictional forces to reduce the amplitude sufficiently. The sonar body should only be raised continuously then if, at any time during the raise procedure, the amplitude lies within a predetermined 'satisfactory raise envelope'. This envelope, which is defined by θ_e as a decreasing function of s_m, is now determined for the Sea King hovering at 12·2 m (40 ft) altitude.

In the Sea King system, the reeling machine is controlled by a three-way switch allowing the sonar body to be raised, held, or lowered. The rate of change of cable length is defined by the function $f_K(s_m)$, where $K = -1$ for raising, $= 0$ for holding, $= 1$ for lowering. In air,

$$f_{-1}(s_m) = -1{\cdot}5\ \text{m/s}\ (-5\ \text{ft/s})^* \quad \text{for } s_m > 3\ \text{m}\ (10\ \text{ft})$$

$$= -0{\cdot}3\ \text{m/s}\ (-1\ \text{ft/s}) \quad \text{otherwise}$$

$$f_0(s_m) = 0$$

$$f_1(s_m) = 2{\cdot}4\ \text{m/s}\ (8\ \text{ft/s})$$

So far, when simulating the raise procedure, conditions have been assumed known at the beginning. However, in determining the 'satisfactory raise envelope', it is convenient to obtain θ_e for conditions specified at the end. This is readily achieved by reversing the integration process so that the 'final' conditions become 'initial' conditions. Hence, at $s_m = 0$, initial conditions were set with $\dot{\theta} = 0$ and $\theta = \theta_{eo}$ for a range of values of θ_{eo} up to 30°, and with θ_{aft} and θ_{for} both set equal to θ_{lim} (= 12°), which is defined as the mean value of θ_{aft} and θ_{for}. The fore and aft symmetry resulting from the latter assumption allows an envelope curve to be drawn touching the maximum values of θ experienced during the simulation. Values of θ_e/θ_{eo} were read from the curves at intervals in s_m of 2·4 m (8 ft) and were found to be almost independent of the value of θ_{eo} assumed. Figure 3 shows the curve obtained when $\theta_{eo} = 12°$. In the region where damping is required, i.e. for $s_m > 3$ m (10 ft) (see below), the curve is well approximated by the straight line

$$\theta_e/\theta_{eo} = -0{\cdot}076\, s_m/d_t + 0{\cdot}69 \tag{5}$$

which is also shown in Figure 3. Hence, for θ_{eo} specified in advance, θ_e is readily obtained from Equation (5) as a function of s_m.

In a fully three-dimensional representation, cable angle displacements in both pitch and roll would be required. However, for the two-dimensional model assumed, only pitch angle is considered. Because a true measurement of the angle below the funnel is not available when funnel snagging occurs, an automatic procedure must be able to effectively predict the motion during snagging from measurements recorded prior to snagging. For a particular oscillation, if $\dot{\theta}$ is known when the cable is vertical, the model describing the complete system, represented by Equation (4), could be used to predict the motion for the following half-period when the cable is vertical again. However, calculations would need to be performed by a suitable microprocessor within the measurement sampling time (say 0·05 to 0·1 s). Without further approximations, Equation (4) can only be solved numerically, so that the real time requirement for a solution would be difficult to satisfy. Hence it is necessary to obtain a very simple model giving estimates for the amplitude and half-period of oscillation in the form of analytical expressions. Given the estimate of amplitude, θ_1, sufficient damping will have occurred when $\theta_1 < \theta_e$. The estimate of half-period of oscillation, t_1, allows times to be set at which raising and lowering is to stop and start. Such a model required by the microprocessor is given by assuming that the pendulum length is constant during each half-period and is equal to a suitably derived mean value. The estimated mean value, $\hat{s}$, would need to take account of reduction in the effective pendulum length caused by snagging and any net rise in height of the body. It was found necessary to modify the method for calculating $\hat{s}$ each time the raise procedure was changed. Hence, for the time being, $\hat{s}$ is assumed known. Let t be the time from the last instant at which the cable was vertical (termed 'reset' time). Consider the oscillation of a simple pendulum from $t = 0$, where $\theta = 0$ and $\dot{\theta} = \dot{\theta}_o$ to $t = t_1$, where $\theta = \theta_1$, and $\dot{\theta} = 0$. Using the conversation of energy principle,

$$mg\hat{s}\,(1 - \cos\theta_1) = \tfrac{1}{2}\, m\hat{s}^2\dot{\theta}_o^{\,2} \tag{6}$$

which gives

$$\dot{\theta}_o = 2^{\frac{1}{2}}\hat{\omega}\,(1 - \cos\theta_1)^{\frac{1}{2}} \tag{7}$$

where $\hat{\omega}$ is the estimated angular frequency of oscillation, equal to $(g/\hat{s})^{\frac{1}{2}}$. Using the small angle approximation $\cos\theta_1 = 1 - \frac{1}{2}\theta_1^2$,

---

* Although S.I. units are shown as the primary units with Imperial units following in parentheses, calculations are performed using Imperial units since they are used throughout the helicopter control systems documentation.

$$\theta_1 = |\dot{\theta}_o| / \hat{\omega} \tag{8}$$

Comparing $|\dot{\theta}_o|/\hat{\omega}$ in Equations (7) and (8), errors at $\theta_1 = 30°$, $60°$, and $90°$ are 1%, 5%, and 11% respectively.

The quarter-period of oscillation is given by $t_1 = \frac{1}{2}\pi/\hat{\omega}$. The definition of times at which the sonar body is lowered, held, or raised during a half-period oscillation are shown in Figure 4. Also defined are the lower, hold, and raise time intervals. The problem is to determine optimum values of the lower to raise time ratio $\lambda_{\ell r}$ $(= \Delta t_\ell/\Delta t_r)$ and hold time ratio λ_h $(= \Delta t_h/t_1)$. The times at which lowering and raising are started and stopped are then given in terms of these ratios by

$$t_{\ell A} = \lambda_{\ell r}(1 - \lambda_h)\, t_1/(1 + \lambda_{\ell r}), \qquad t_{\ell B} = 2t_1 - t_{\ell A}$$

$$t_{rA} = t_{\ell A} + \lambda_h t_1, \qquad t_{rB} = 2t_1 - t_{rA}$$

It is desirable to have the least number of changes between raising and lowering so that both mechanical wear and time penalty are kept to a minimum. Other constraints are that the sonar body should not be lowered back into the sea or raised to the trail position before sufficient damping takes place. The most suitable value of $\lambda_{\ell r}$ will depend on the raise and lower speeds. In simulations of the Sea King system, it was found to be desirable to complete damping before the raise speed changed when $s_m < 3$ m (10 ft) so that a constant raise to lower speed ratio could be assumed. It was found best to set $\lambda_{\ell r}$ equal to the constant speed ratio of 0·625 with $\lambda_h = 0$ (i.e. $t_{\ell A} = t_{rA} = 0{\cdot}38\, t_1$), and to raise the sonar body a sufficient distance above the sea before first lowering. In practice though, it may be necessary to set λ_h to some small non-zero value to minimize load effects on the winding mechanism when suddenly switching between raising and lowering.

In the method adopted, once the sonar body is well clear of the water, new values of $t_{\ell A}$, $t_{\ell B}$, t_{rA}, and t_{rB} are calculated each time the cable is vertical. This would result in a change between raising and lowering at the beginning of the first oscillation (i.e. at $t = 0$) and at the end of the final half-period oscillation (i.e. at $t = 2t_1$) in which damping is required. To minimize the number of changes between raising and lowering, nether of these transitions are made.

In the following method for calculating $\hat{s}$, various corrections are made. These were found necessary mainly because of the sensitivity of changes in height of the sonar body to the correct determination of t_1 from $\hat{s}$. Any difference between the estimate t_1 and the actual quarter-period of oscillation given by the mathematical model of the complete system will result in either a shortened or lengthened final lowering period during each half-period oscillation (see Fig. 4). Hence, for $\lambda_{\ell r}$ set equal to the raise-to-lower speed ratio, this could result in an undesirable change in height of the sonar body while damping occurs.

An initial estimate of the correction, $\hat{s}_c$, to s_m is given, on reference to Equation (2a), by

$$\hat{s}_c = a + d_t \tag{9}$$

Using the relation

$$\hat{s} = s_m + \hat{s}_c \tag{10}$$

initial estimates $\hat{\omega}$, t_1, and θ_1, are calculated. If snagging is indicated using the initial estimate θ_1, i.e. if $\theta_1 > \theta_{lim}$, then a linear adjustment for $\hat{s}_c$ is made which is proportional to the amount by which θ_1 exceeds θ_{lim}, i.e.

$$\hat{s}_c = \hat{s}_c - d_f(1 - \theta_{lim}/\theta_1) \tag{11}$$

Because the body is not lowered in the initial quarter-period oscillation in air, there is a significant gain in altitude of the body. Hence, for the initial half-period oscillation, a further adjustment is made to $\hat{s}_c$ in the form

$$\hat{s}_c = \hat{s}_c + t_1 f_1(s_m) \tag{12}$$

Where appropriate, these adjustments are then used to give final estimates $\hat{s}$, $\hat{\omega}$, t_1, and θ_1.

In Appendix A, flow charts giving the complete procedure are shown together with constants appropriate to the Sea King system. By initially setting K equal to +1, the procedure allows the body to be continuously lowered into the water. It can be seen that once the variable e is changed from 0 to 1 in the procedure, the body is continuously raised or lowered without any

constraints. An inherent property of the procedure is that the required damping will always be achieved, but at some cost in time and mechanical wear caused by changes between raising and lowering. A number of simulations were made for the Sea King system to obtain an indication of performance. Figure 5 gives an example of one of these simulations. For the same parameter values, Figure 6 shows 'raise time', t_r, and 'number of lowers', n_ℓ, at 1° intervals in $\theta(0)$ between 0° and −30°. Negative values of $\theta(0)$ are thought to be more likely in view of the usual direction of the surface current for the helicopter heading into wind.[7] However, since the only deviation from fore and aft symmetry is in a 3° funnel inclination, results are not expected to differ significantly for a sign reversal in $\theta(0)$. Figure 6 shows that no damping is required for $-\theta(0) < 3°$ in which case the body is raised continuously, taking 16 s. The oscillating nature of the increase in raise time is due mainly to the way corrections to $\hat{s}$ are made when allowing for funnel snagging, the estimate directly affecting the values obtained for $t_{\ell A}$, $t_{\ell B}$, t_{rA}, and t_{rB}. Generally, for the purpose of judging performance of the method, it is sufficient to smooth out these oscillations by fitting curves as shown. Similarity between the curves in Figures 6a and 6b is readily seen, which is to be expected because of the fairly direct relationship between t_r and n_ℓ. For values of θ_{eo} up to 30°, the relationship was found to be fairly well represented empirically by the equation

$$t_r = 3n_\ell + 16 \qquad (13)$$

where t_r is in seconds. In Figure 7 therefore, performance results for each of the values of θ_{eo} selected are represented by a single curve which may be used to give an approximate value for either quantity.

4. CONCLUDING REMARKS

When winching a sonar body from the sea to the trail position beneath the helicopter, growth in amplitude of oscillation can result in 'ball strike'. The proposed procedure for overcoming the problem is to raise and lower the body alternately during defined periods of each oscillation. When sufficient damping is achieved, the body is raised continuously to the trail position. Natural damping in the system through aerodynamic and frictional forces, which are neglected in the model, will in practice reduce amplitudes of oscillation below those predicted. On the Sea King Mk.50 helicopter, the sonar operator is unlikely to be able to manually perform the above procedure satisfactorily because insufficient information is displayed. Hence, an automatic system is proposed. Because the procedure will always control damping to a prescribed degree, then, apart from mechanical wear, performance can only be judged by the amount of additional time required to raise the body to the trail position. For the Sea King, results presented show the variation of time penalty with initial angular displacement and required maximum amplitude at the trail position. These results would generally apply to three-dimensional motion, since the periods of oscillation are similar. An increase in mechanical wear on the winding mechanism would generally be expected to be proportional to the number of changes between raising and lowering, which is shown to be proportional to the increase in raise time. To reduce cable wear when raising the sonar body while the cable touches the funnel rim, it may be necessary to reduce friction in some way, such as by fitting rollers to the funnel rim. Although increases in raise time and wear in the winding mechanism and in the cable may prevent practical application of the method, the study clearly demonstrates how to help avoid ball strike when manually raising a sonar body. In particular, the natural tendency of sonar operators to raise a wildly swinging sonar body only while the body is close to the vertical is shown to be the most effective way of increasing swing amplitude and hence the risk of ball strike.

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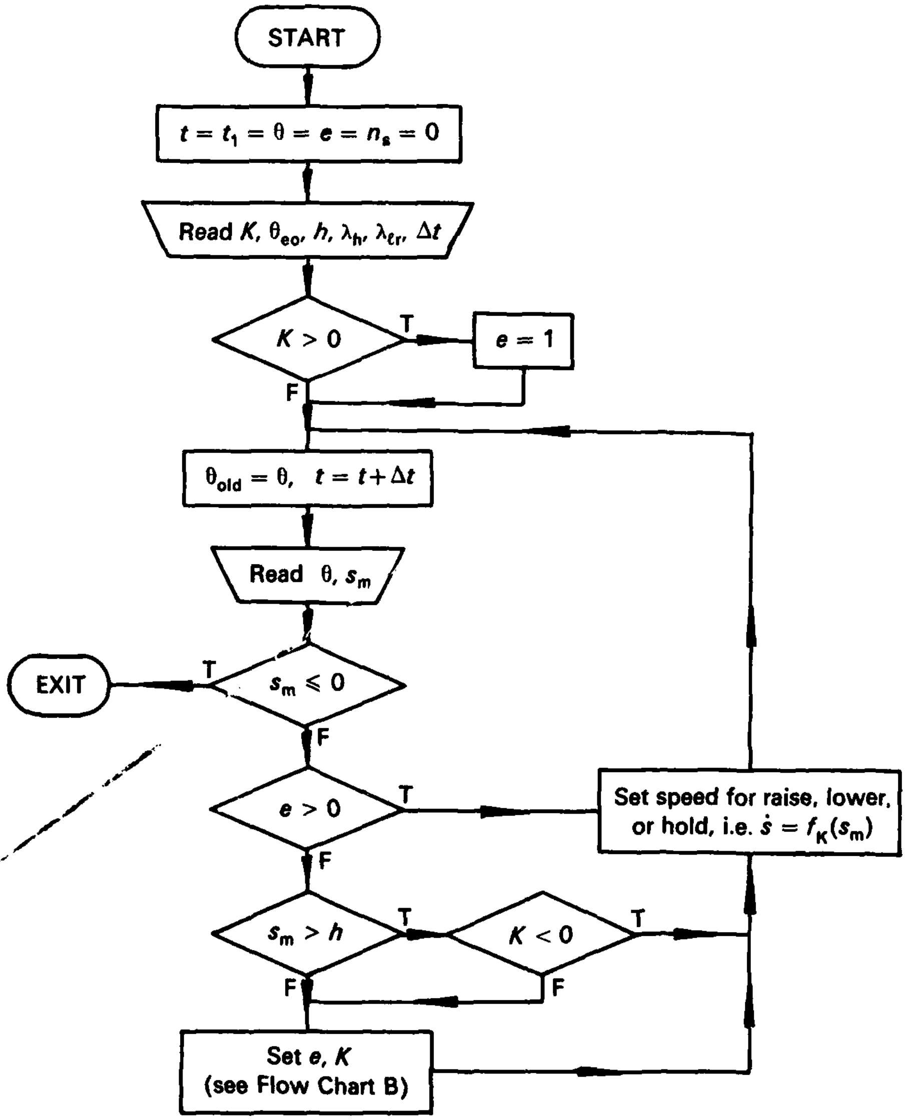
APPENDIX A
Damping Procedure Flow Charts

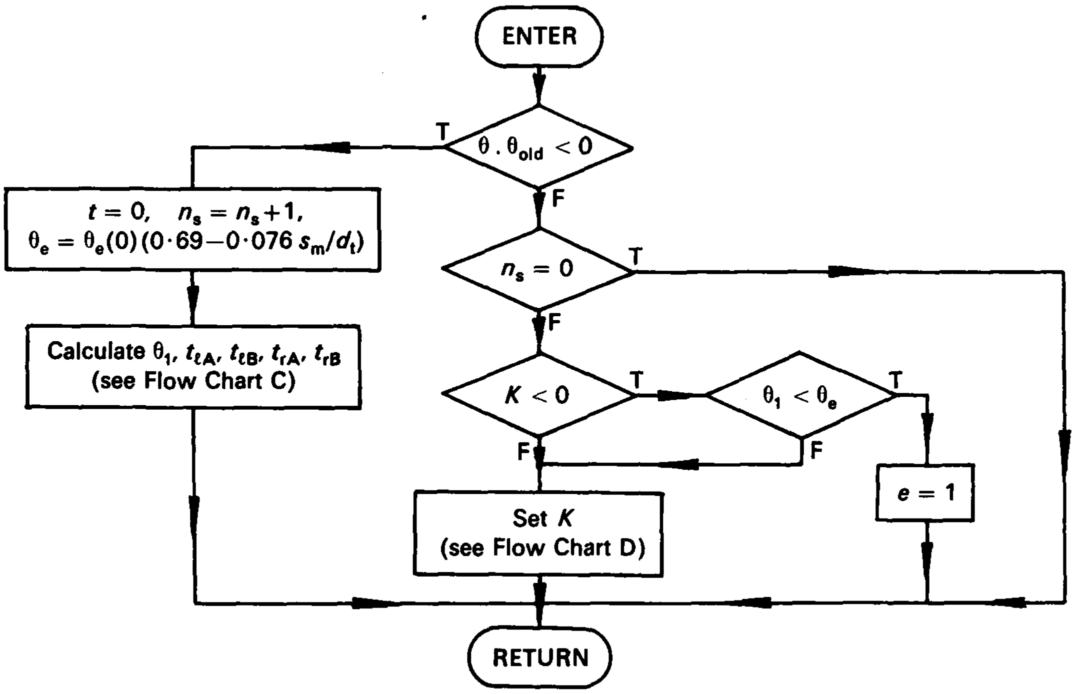
(1) Flow Chart A—Main Flow



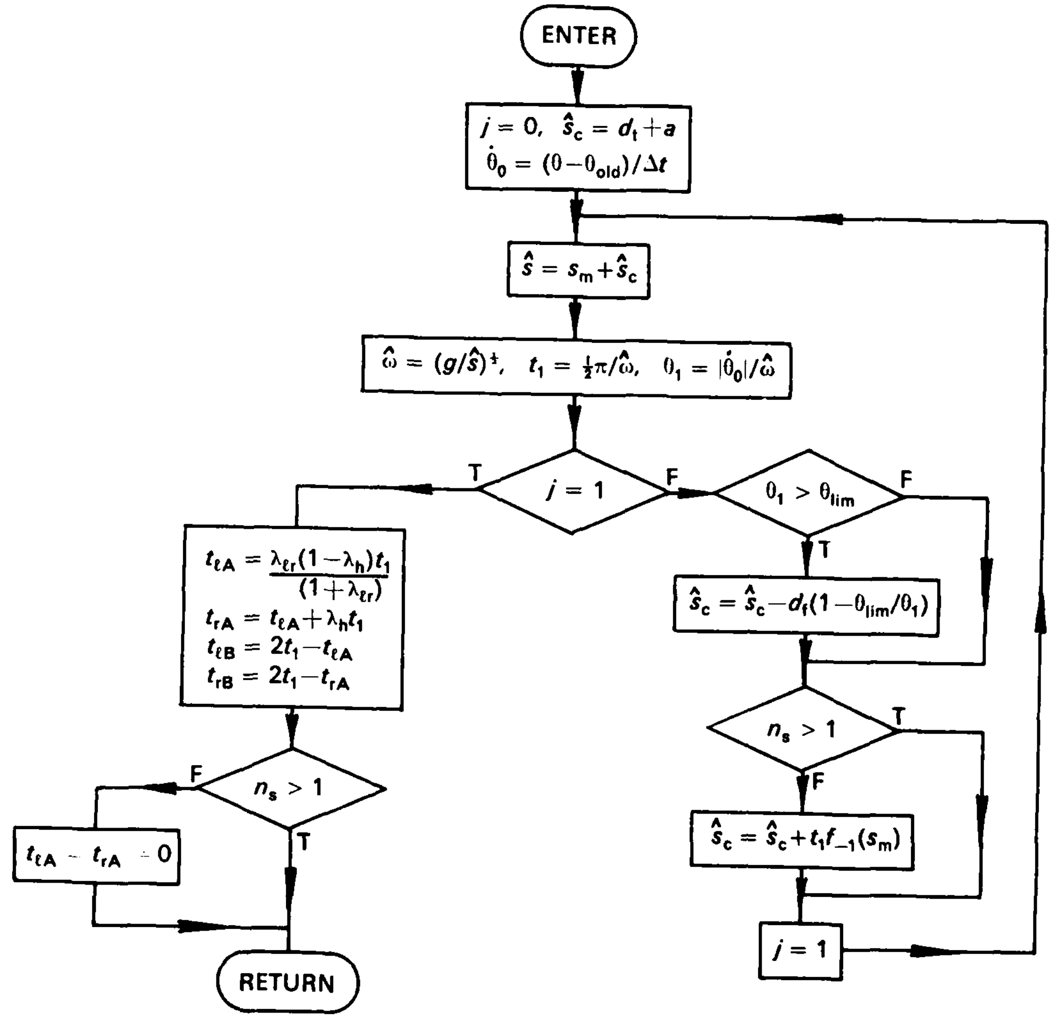
$e = 0$ (raise, lower, or hold to reduce swing amplitude)
$= 1$ (raise or lower continuously)

$K = -1$ (raise)
$= 1$ (lower)
$= 0$ (hold)

(2) Flow Chart B—Set e and K



(3) Flow Chart C—Calculate θ_1, $t_{\ell A}$, $t_{\ell B}$, t_{rA}, and t_{rB}



Constants:

$a = 0{\cdot}7$ m (2·4 ft)

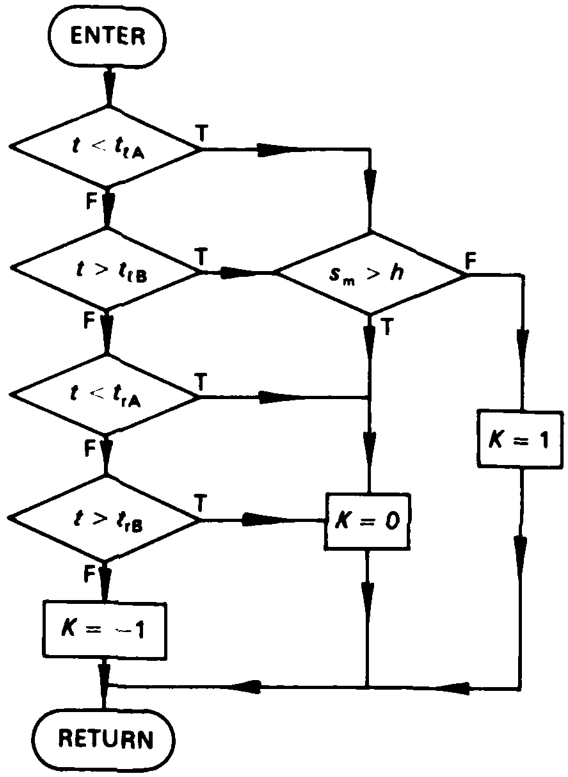
$d_f = 1{\cdot}9$ m (6·3 ft)

$d_t = 2{\cdot}3$ m (7·6 ft)

$g = 9{\cdot}81$ m/s^2 (32·2 ft/s^2)

$\theta_{lim} = 12^{\circ}$

(4) Flow Chart D—Set K



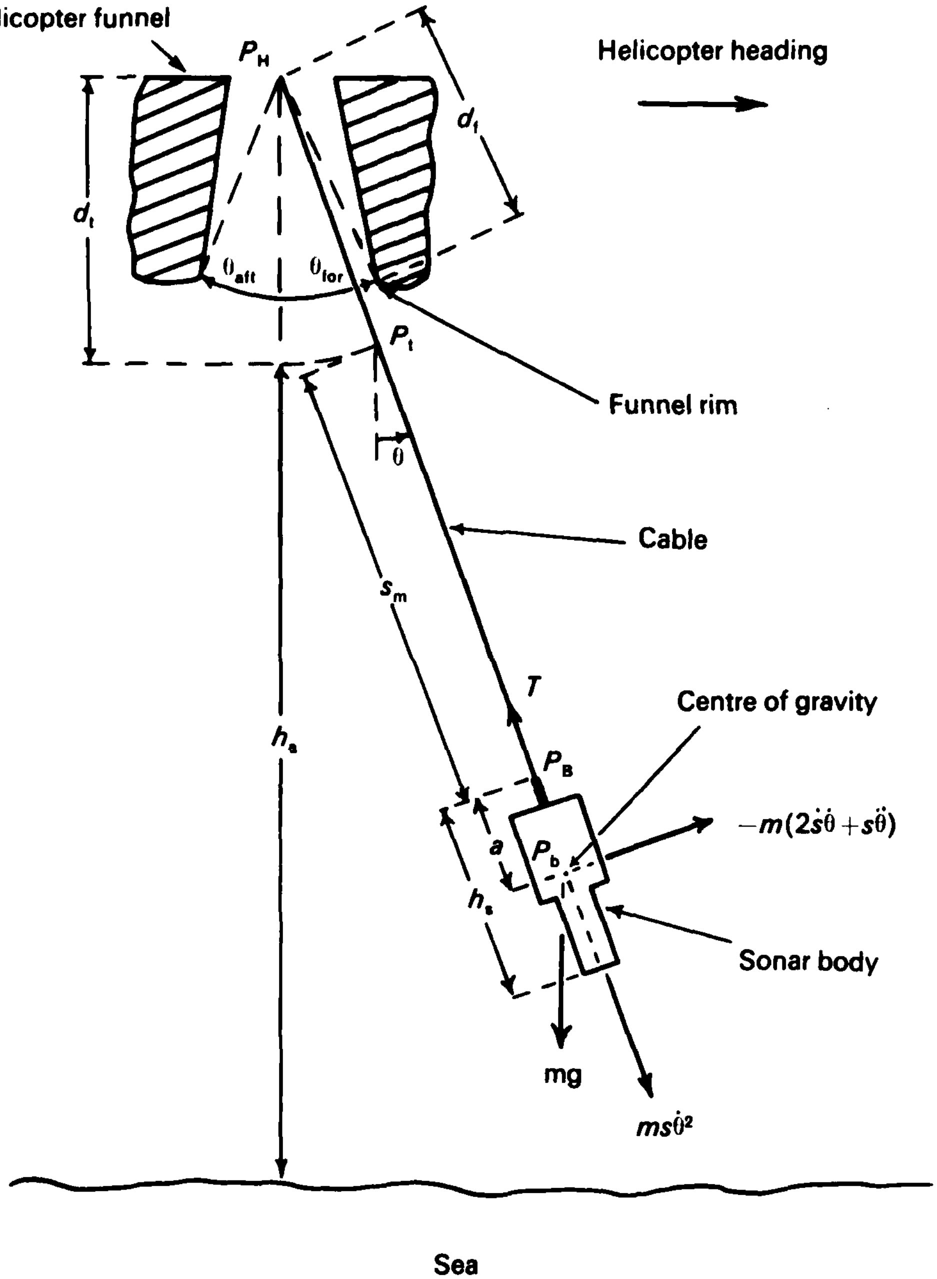


FIG. 1: SIDE VIEW OF SWINGING SONAR BODY. FORCES ACTING ON SONAR BODY ARE SHOWN, WHERE s IS EFFECTIVE CABLE LENGTH AND $\dot{s}$ IS CONSTANT

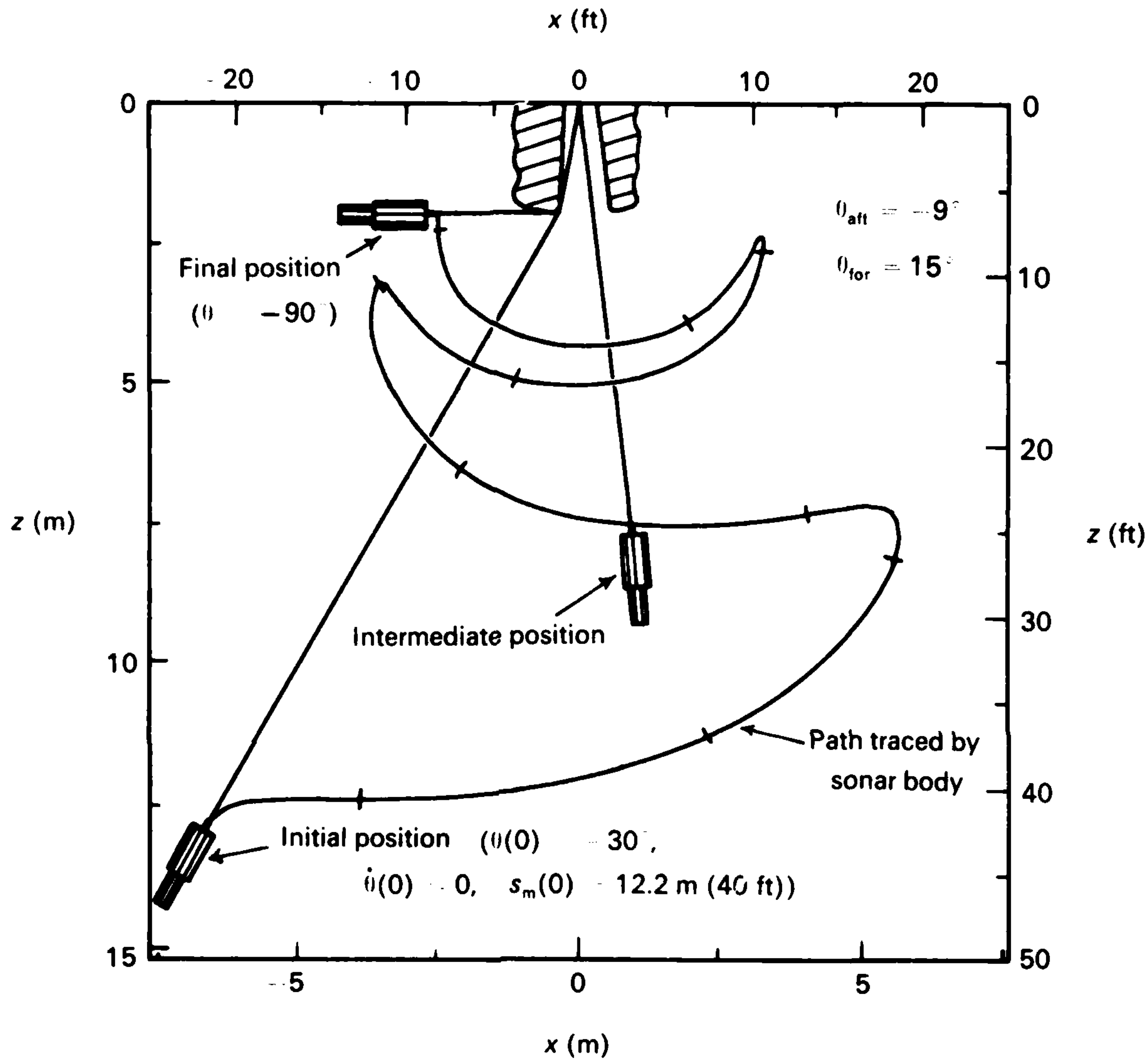


FIG. 2: EXAMPLE OF BALL STRIKE WHEN CONTINUOUSLY RAISING SONAR BODY. TICK MARKS REPRESENT 1 SECOND INTERVALS

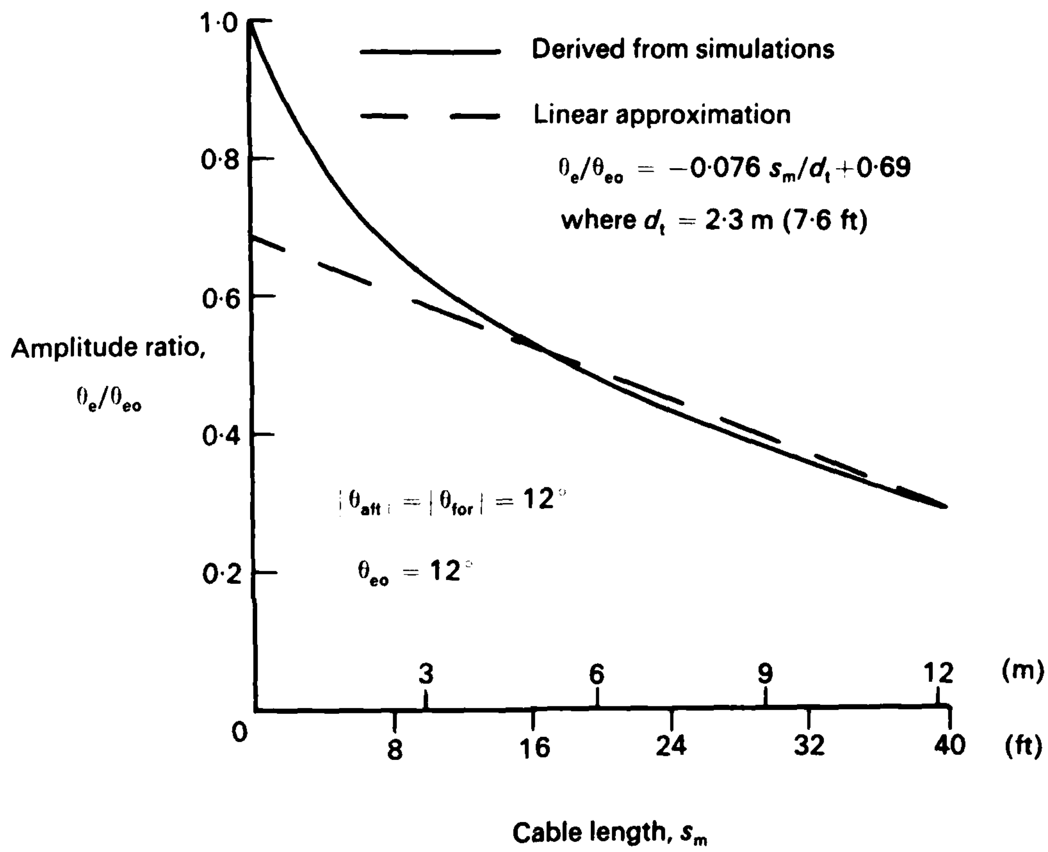


FIG. 3: AMPLITUDE RATIO DEFINING SATISFACTORY RAISE ENVELOPE

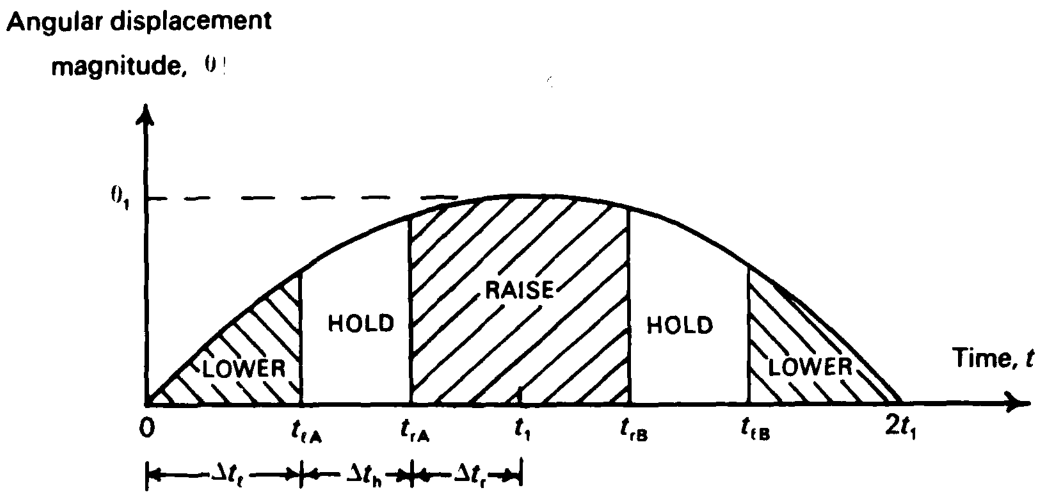


FIG. 4: SPECIFICATION OF 'LOWER', 'HOLD', AND 'RAISE' REGIONS IN A HALF-PERIOD OSCILLATION

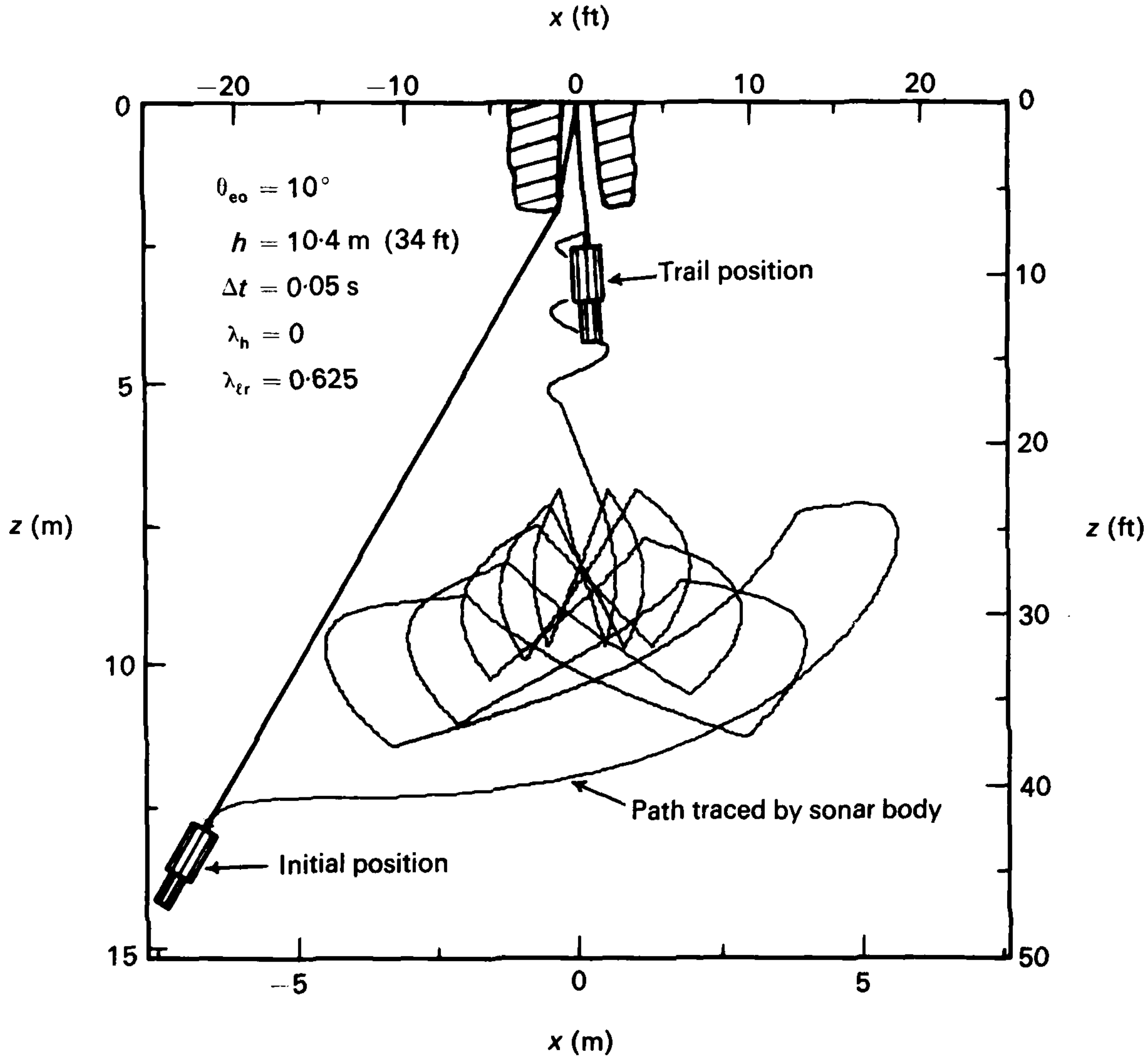


FIG. 5: DAMPING PROCEDURE APPLIED TO EXAMPLE GIVEN IN FIG. 2

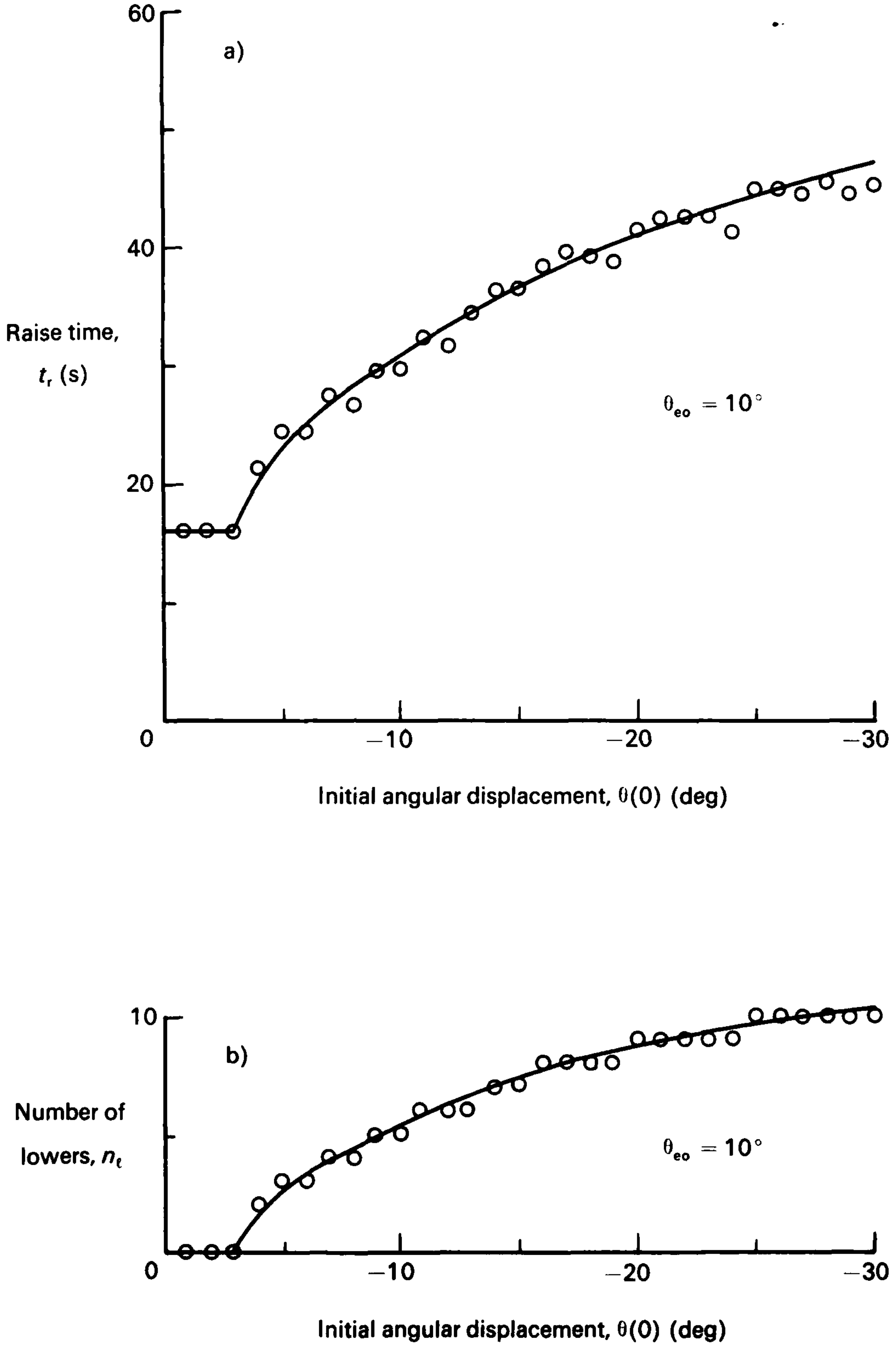


FIG. 6: RAISE TIME AND NUMBER OF LOWERS USING DAMPING PROCEDURE

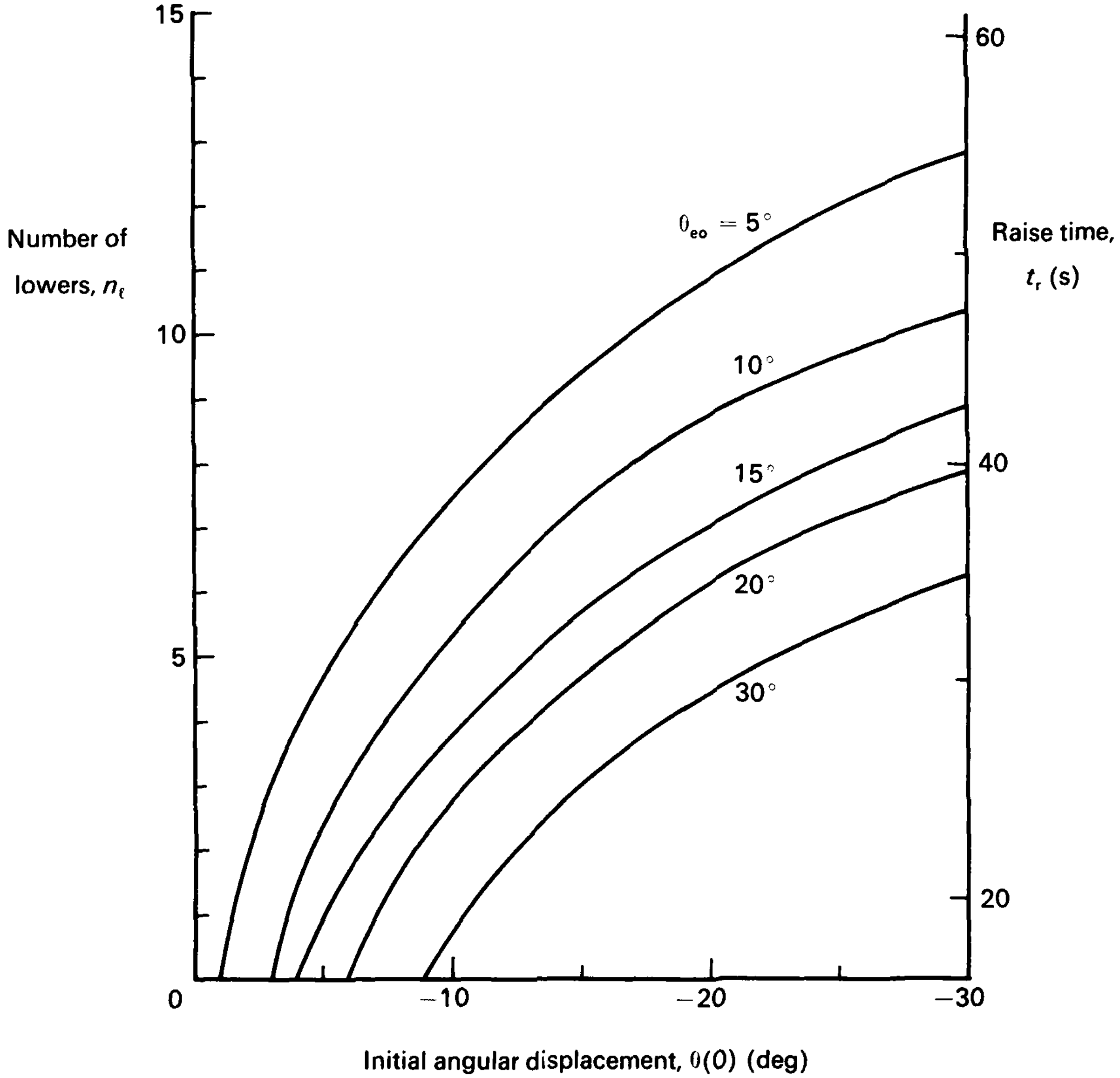


FIG. 7: PERFORMANCE CURVES FOR NUMBER OF LOWERS AND RAISE TIME

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